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TECHNICAL REPORT ARCSL-TR-79022

METHODOLOGY FOR ESTIMATING SMOKE/OBSCURANT MUNITION EXPENDITURE REQUIREMENTS

by

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April 1979

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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(U) Methodologies have been developed and, where possible, implemented in computer programs for estimating smoke munition expenditure requirements under a broad range of operational conditions. The techniques are based on idealized geometries and simplifying assumptions which are expected to overestimate requirements by an undeterminable margin. Validation of the estimates is desirable but has not been attempted. The techniques are designed to be used with any smoke-effect simulation model capable of providing information on effective screen size as a function of time.

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PREFACE

The work described in this report was authorized under Technical Area 4-3, Smoke Technology. This work was started in May 1978 and completed in December 1978.

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I. INTRODUCTION.

For the last few years, the US Army has expended a large effort to improve its ability to create and utilize smoke/obscurant screens in the battlefield against enemy electro-optical target acquisition devices. A key aspect in the research and development process is the analysis of potential effectiveness of developmental systems. Since most of the technology of electro-optics has been developed since World War II and since little interest was paid to smokes/obscurants until the 1973 Arab-Israeli conflict, the methodology to support systems analysis studies has been developed only recently. This methodology has been concentrated in the many models which attempt to simulate smokes/obscurants in the battlefield. Techniques have been developed to relate simulated performance to measures of effectiveness, but little documentation of these techniques has appeared. The purpose of this report is to disseminate some analytical tools developed at Chemical Systems Laboratory to support systems analysis studies of developmental smoke munitions.

Smoke munitions effectiveness estimates are usually based upon munition expenditure requirements to accomplish a screening mission. The mission is normally described in terms of the target to be screened from observers located along a front; i.e., the specific location of the observer(s) is assumed to be unknown, therefore a front line must be screened. The target's background, the natural and artificial sources of radiant illumination may be specified, along with the target acquisition device, e.g., unaided eye, binoculars, electro-optical (EO) imager. A variety of meteorological conditions, which strongly affect munition performance, may be considered. In an idealized study, only crosswind and headwind/tailwind conditions are considered. Quartering/flank wind conditions lead to expenditure requirements between the two extremes.

For a specified screening mission, there is probably a minimal set of optimum aiming points at which multiple rounds should be fired to accomplish the mission. However, the complexity of simply stating the associated constrained optimization problem is beyond practical consideration. One might consider a trial-and-error approach by simulating the firing of multiple rounds at a set of arbitrary aiming points. A more practical approach is to estimate the performance of a single munition (or submunition) under the conditions of the mission and use some systematic method to estimate the number of munitions required to screen the front. The development of such methods is the subject of this report.

II. BASIC CONCEPTS.

A. Instantaneous Sources.

When a smoke agent is released over a very short time, say less than 1 second, it is considered an instantaneous volume source with some initial cloud dimensions. If a horizontal plane containing all lines of sight at a given height passes through the cloud, the intersection of the cloud boundary with the plane is a closed curve bounding an area. For a Gaussian cloud, which is assumed in this methodology, the effective cloud boundary is defined by the set of points at which some property of the cloud has a specified minimum value. Depending upon the obscuring mechanism involved, the critical property may be concentration, the integrated concentration (CL), the reduced contrast resulting from the obscuring power of the cloud, or the transmittance through the

cloud. The maximum width of the bounded area, measured normal to the line of sight, is defined as the effective screen width of the cloud at the height of the line of sight at the instant in time.

As time increases, the cloud expands due to turbulent diffusion and is transported downwind at the prevailing windspeed. The effect of these phenomena is to cause the effective screen to grow while moving laterally. The estimation of munition expenditure requirements thus consists of two basic tasks: (1) prediction of effective screen width as a function of time and (2) selection of the number and locations of a set of aiming points which will be expected to cause a specified front to be screened as of some time after the initial round or rounds function.

B. Continuous Sources.

The most effective smoke screening systems today make use of continuous sources, which emit smoke over a long time interval. Theoretically, smoke generators can operate indefinitely, but actually all real systems emit for a finite time, usually referred to as the burning time (t_B). Many new munitions deliver a set of submunitions, ranging in number from 6 to 92.

A single continuous source produces a smoke cloud shaped like a long cone lying on its side with the vertex at the source. The base end of the cone may at some time slow down in its growth rate and tend to form a cylindrical plume parallel to the wind direction. If a crosswind line of sight is to be screened, i.e., a line of observers parallel to the wind, the effective screen length is defined as the distance between the farthest downwind and the least downwind lines of sight which are effectively screened. For a headwind/tailwind line of sight, the effective screen width is defined in the same way as for an instantaneous source. The expected variation with time is different, however, and allows for a simpler technique to estimate munition expenditure requirements.

For munitions with multiple submunitions, the effective crosswind screen length is defined the same as for a single source, but there is no practical way to combine the effects of multiple clouds from randomly located sources by other than simulation techniques. The normal approach to the simulation would be a Monte Carlo technique varying the orientation of the elliptical pattern of submunition locations (impact points) to the wind direction. Hundreds, possibly thousands, of effects estimates would be averaged to obtain an expected effective screen length. Some smoke simulation models, particularly the one used by the author, are computationally too expensive for Monte Carlo methods. The procedure we use attempts to estimate the expected set of impact points which in a single simulation produce the expected effective screen length. The procedure and rationale are described below.

Assume field test data are available for the firing of a single round which releases multiple submunitions, each of which is a continuous source. The impact points are uniformly and randomly distributed in an elliptical area. The ellipse has semi-axes of lengths a and b. The area of the ellipse is πab. The rotation of the ellipse about its center would cause the ends of the axes to circumscribe concentric circles of radii a and b. These circles describe the minimum and maximum dimensions of impact areas which a crosswind line of sight would "see," because it will intersect every downwind plume regardless of the crosswind dimension. We take as an estimate of the expected impact area a circle whose area is that of the ellipse; i.e., $\pi r^2 = \pi ab$. Solving for r gives the radius of the circle as the geometric mean of the semi-axes; i.e., $r = \sqrt{ab}$. Using this circle, one can develop a technique for generating a set of impact points, relative to the center of the circle, which are uniformly, but not randomly, distributed. Once a characteristic impact pattern is generated for a multiple submunition round, the determination of effective screen length is the same for all systems of continuous sources.

III. METHODOLOGY.

A. Instantaneous Sources.

1. Effective Screen Width.

The task of predicting effective screen widths with time may be accomplished in many ways because there are many different models available to simulate smoke munition performance. The reader may have his own technique, but a procedure using ACT (ASL/CSL/TRASANA), a derivative of the original SOM I developed by Johnson,* will be described here.

An instantaneous smoke source released at the origin of a reference system in which x is the downwind direction, y is the crosswind, and z is the height above ground is centered at time t at the point $[(ut, 0, z(t)]$. Its dimensions are expressed in terms of the standard deviations of the spatial distribution of the mass: $\sigma_x(t)$, $\sigma_y(t)$, and $\sigma_z(t)$. Since we are concerned with horizontal screen width, $\sigma_z(t)$ is not involved in this discussion. The boundary of the cloud is an ellipse with the major and minor axes being proportional to σ_x and σ_y. For the purpose of this method, we prefer to assume $\sigma_x(t) = \sigma_y(t)$, which is usually not in serious conflict with reality but has been shown to be false. The rationale for this assumption is the practical desire to use one set of computations for all wind/line-of-sight orientations. With $\sigma_x(t) = \sigma_y(t)$, the cloud has a circular cross section which yields the same effective screen width for all lines of sight.

Let us denote by H(t) the half-width of the effective screen. If one exercises ACT with a set of lines of sight parallel to the x-axis and for a suitable set of t values, assuming for this illustration that relative contrast (C) is the critical parameter to effectiveness, then a matrix of contrast values can be obtained which has the form:

	y_1	y_2	y_m
t_1	C_{11}	C_{12}	C_{1m}
t_2	C_{21}	C_{22}	C_{2m}
.			
.			
.			
.			
t_n	C_{n1}	C_{n2}	C_{nm}

*Johnson, Morris C., and Forney, Paul. Effectiveness of Obscuring Smokes. MUCOM Operations Research Group Report. August 1972. Unpublished.

Suppose an effective screen exists if $C \leq CEFF$. Then for each t_i, one can find by interpolation the value of y for which $C(y, t_i) = CEFF$. (It has been observed that $\ln C = a + b\,y$ is a good model to use for interpolating with relative contrast. Other critical parameters may require other models.) The values of y(t) obtained in this manner are observed values of H(t) if the cloud is initiated at the origin and the $y_j \geq 0$ for all $j = 1, 2, \ldots, m$. It is possible then to use least-squares techniques to obtain a functional model of H(t), perhaps of the form:

$$H(t) = \sum_{k=0}^{\eta} a_k t^k \tag{1}$$

The values of m and n are dependent, of course, on the number of parameters in the H(t) model and the desired resolution.

2. Munition Expenditure Requirement.

For any specified screening mission, there may be many ways to accomplish the mission. The real world, however, imposes many constraints in terms of logistics, human performance limitations, and arbitrary time limitations. To a certain degree, the methodology should accommodate such constraints, but practical considerations may require the use of simplifying assumptions. The assumptions underlying this methodology are as follows:

a. The mission is to form an effective screen within t_0 seconds of initial smoke release along a front of length FRONT and maintain the screen for ST seconds.

b. All munitions are identical in their performance.

c. The delivery system is capable of putting a round on a specified aiming point (zero system error).

d. The fire unit has NTUB delivery systems (artillery tubes, mortars, launchers).

e. Each delivery system may be aimed and fired independently or in salvos, as required.

f. The fire unit has a total load of LD rounds available for the mission.

g. The minimum time between successive fires is TMU seconds.

h. The fire unit can maintain its maximum fire rate for TUM seconds, after which no fire is possible.

i. The aiming points must be at least 100 m from friendly troops to avoid accidental friendly casualties from impacting munitions.

j. A fixed geometry exists with the lines of sight normal to two parallel fronts, one for friendly targets and one for enemy observers.

k. The wind direction forms an acute angle θ with the fronts, i.e., $0 \leq \theta \leq 90°$.

These simplifying assumptions lead to the development of a technique for estimating munition expenditure requirements for the specified mission.

Since the half-width function H(t) was defined earlier to be independent of the wind direction/line-of-sight angle, the reference system for this methodology can be defined to facilitate reader understanding. The front to be screened is defined parallel to the x-axis with x = 0 being the upwind edge of the front. The positive y-axis is normal to the front in the upwind direction. The components of the wind vector are then expressible in terms of their relation to the front; i.e.,

$$u_x = u \cos \theta \tag{2}$$

$$u_y = u \sin \theta \tag{3}$$

This reference system provides the ability to identify aiming points as being upwind or downwind of the front. The distance between the two fronts is the range (R).

The formation of a smoke screen is a dynamic process. The mission requires the front to be screened within t_0 seconds. If $u_y > 0$, the screen must be formed before the clouds travel halfway to the front to allow time for replenishment without gaps in the screen. Since the effective width of a cloud reaches a maximum at some time t_m, the screen must be formed prior to that time. Hence the maximum allowable time t* to form the screen is the least of the three times; i.e.,

$$t^* = \min \left\{ t_0, t_m, \frac{R - 100}{2u_y} \right\} \tag{4}$$

The minimum number of rounds required to establish the screen can now be estimated from the width of a single cloud at time t*, which is 2H(t*). The minimum number is

$$N = \frac{\text{FRONT}}{2H(t^*)} \tag{5}$$

which must be increased by one if there is a fractional round required. At this point, one must consider the constraints. If N > NTUB, more than one salvo must be fired to establish. For the moment, let us proceed with the N ≤ NTUB case. We know that a single salvo will establish the screen. This is the simplest case for which the replenishment of the screen can be considered. The

initial set of aiming point coordinates for NSE establishment salvos are expressed as (x_i,y_i):i=1,2,. . N, where

$$x_i = \text{FRONT} - (2i-1)\,[H(t^*)] - u_x t^*$$

$$y_i = u_y\,[t^* + \text{TI}\,(\text{NSE}-1)] \tag{6}$$

The y_i values are the minimum setback distances required to place the screen between the fronts. The time TI is the interval between salvos when NSE > 1. In order to maintain the screen for ST seconds, it is necessary to fire NTUB′ rounds every TI seconds. If t_m is sufficiently large, NTUB′ may be less than NTUB, thus freeing some delivery systems from the smoke mission. The trade-off between choosing TI large or NTUB′ small is difficult. Since at t = t* the most upwind cloud is passing the upwind edge of the front, TI < t* is essential. Let us choose TI = t*/NSR so that as few as N/NSR clouds must be replaced. Since NSR = 2 yields the largest TI = t*/2 and NTUB′ = (1 + sin θ) N/2, the only remaining question is whether the cloud starting at x_N will screen the downwind edge of the front when it gets there. This is assured when the minimum setback distance $y = u_y\,(t^* + \text{NSR} \cdot \text{TI})$ and

$$\frac{\text{FRONT} - x_N}{u_x} < t_m \tag{7}$$

If equation 7 is not satisfied, then the most upwind aiming point that satisfies equation 7 must be found by finding the x_i so that

$$t' \doteq \frac{\text{FRONT} - (2i-1)\,H(t^*) - u_x t^*}{u_x} < t_m \tag{8}$$

It must be noted also that NSR can be chosen as 2 only if t*/TMU ⩾ 2 since the unit's capability is a limiting factor. In some cases, therefore, NSR = 1 is required. If all necessary conditions are satisfied, then

$$\text{NTUB}' = \max\left\{1, N - i + \frac{[1 + \text{NSR} - 1)\sin\theta]}{\text{NSR}}\right\} \tag{9}$$

The maximum duration of the screen is determined from the constraints to be

$$T_{max} = \min\left\{\frac{t^*}{\text{TMU}}, \frac{\text{LD} - \text{N}}{\text{NTUB}'} \cdot \text{TI}\right\} \tag{10}$$

Now let us turn to the case of $NSE > 1$; i.e., $NTUB < N$. Of primary concern is whether the fire unit is capable of accomplishing the smoke mission. The minimum time to establish is t^* just as in the $NSE = 1$ case. At the maximum fire rate, the maximum possible value of NSE is

$$NSE_{max} = \| 1 + t^*/TMU \|^* \tag{11}$$

Determination of the required value of NSE must consider the staggered arrival time of the salvos and the possibility that some aiming points may not require repeated firing. With the maximum fire rate assumed, the time between salvos is TMU. In this interval, a cloud travels a distance of $u_x \cdot TMU$. The separation between aiming points is $2H[t^* - TMU \cdot (NSE-1)]$, which arises from the fact that the last clouds to arrive have only $t^* - TMU \cdot (NSE-1)$ seconds to grow before reaching the upwind edge of the front. The aiming points are held constant to permit the maximum fire rate, if required. Denote by h the value of $H[t^* - TMU \cdot (NSE-1)]$. Then each salvo after the first could produce

$$NOLAP = \frac{u_x \cdot TMU}{2h} \tag{12}$$

duplicate clouds. The number of salvos required to establish the screen is determined by solving

$$NSE = \frac{FRONT}{2[(NTUB - NOLAP) \cdot NSE + NOLAP]\,h} \tag{13}$$

The equivalent problem to solve is $G(NSE) = 0$, where

$$G(NSE) = [(NTUB - NOLAP)NSE + NOLAP]\; H\,[t^* - TMU \cdot (NSE-1)] - .5\,FRONT \tag{14}$$

If $G(NSE_{max}) < 0$, then the unit cannot accomplish the mission. If $G(NSE_{max}) = 0$, $NSE = NSE_{max}$. If $G(NSE_{max}) > 0$, then the smallest value of NSE for which $G(NSE) \geqslant 0$ should be used.

If the inequality

$$H[t^* - TMU \cdot (NSE-1)] - \frac{FRONT}{2[(NTUB - NOLAP)\,NSE + NOLAP]} \geqslant 0 \tag{15}$$

is not satisfied, the unit cannot accomplish the mission. Also, if $NOLAP \geqslant NTUB$, the mission cannot be accomplished because the unit can never replace all the clouds required.

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*The notation $\| x \|$ denotes the largest integer in x.

It should be recognized that if $NSE < NSE_{max}$, then the maximum fire rate may not be required for the mission. The time between salvos could be increased to

$$TI = \max[TMU, t^*/NSE] \tag{16}$$

and the maximum time this rate of fire could be maintained would be increased theoretically to

$$TUM' = \max\left[TUM, \left(\frac{TI}{TMU}\right) \cdot TUM\right] \tag{17}$$

based on a constant number of rounds fired.

A consideration of the maintenance of the screen takes the above results into account. At the maximum fire rate, the number of replenishment salvos available is $(NSE_{max} - NSE)$, denoted by NSR_{max}. The adjustment to TUM may be sufficient to increase NSE_{max} and is made by substituting TUM′ for TUM in equation 11. The new value of NSR_{max} is

$$NSR_{max} = NSR_{max} + \left[1 + \frac{TUM'}{TMU} - NSE_{max}\right] \tag{18}$$

A further modification of NSR_{max} is possible if NTUB > NTUB′. Then one can assume that more than one delivery system (tube) can be aimed at a particular aiming point and fired in rotation to replenish the screen. Hence, NSR_{max} can be adjusted by a factor of NTUB/NTUB′. The maximum duration of the screen is obtained by considering the limiting factors of performance and logistics in the expression

$$T_{max} = TI \cdot \min\left\{NSR_{max}\left(\frac{NTUB}{NTUB'}\right), \frac{LD - NSE \cdot NTUB}{NTUB'}\right\} \tag{19}$$

Several cases were noted above in which the fire unit is not capable of establishing the required screen in the t* seconds allowed. Rather than dismissing the mission as impossible, an analyst would prefer to examine the problem with a weaker constraint on the value of t*, which is usually specified arbitrarily. The only constraint that will be imposed on t* is that $t^* \leq t_m$. If $t^* > t_m$, the clouds would be decreasing in width at the time they must be merging. The minimum possible value of t* must satisfy equation 15. Of course, if $t^* = t_m$ does not satisfy equation 15, then it is reasonable to conclude the unit cannot provide the required screen. If a $t^* < t_m$ does exist, then NSE_{max} becomes

$$NSE_{max} = 1 + \left|\left| \frac{\min(TUM, t_m - t^*)}{TMU} \right|\right| \tag{20}$$

and NSR_{max} can be adjusted accordingly. If NSE > NSE_{max} even after this adjustment, then the unit cannot provide the screen. Otherwise, the procedure followed with the initially specified t* can be used to estimate the expenditure requirements.

Once the values of NSE, NTUB', NOLAP, and t* have been determined by the appropriate method, it is necessary to determine the number of rounds required both to establish the screen and to maintain it for ST seconds. It is also possible to specify a set of aiming points which will accomplish the mission. For NSE > 1, NTUB' = NTUB, but not all tubes repeat fire at a single aiming point. Some tubes must fire at new aiming points determined by the value of NOLAP. Consequently, we must specify the coordinates for the i-th salvo and the j-th tube. The x_{ij} values are given by

$$x_{ij} = \mathrm{FRONT} - (2\,k - 1)\,H\,[t^* - \mathrm{TI(NSE)}] - u_x\,t^* \tag{21}$$

where

$$k = j \cdot \mathrm{NTUB} - (j - 1)\,\mathrm{NOLAP} \tag{22}$$

The corresponding y_{ij} values are

$$y_{ij} = u_y\,[t^* - \mathrm{TI\,(NSE - 1)}] \tag{23}$$

If NSE = 1, only the y_{ij} values are different, being given by

$$y_{ij} = 2\,u_y\,t^* \tag{24}$$

but the aiming points for replenishment fire are only those for which

$$j > \mathrm{NTUB} - \mathrm{NTUB'} \tag{25}$$

If the required duration ST of the screen is less than the maximum possible, T_{max}, the number of rounds required to accomplish the mission is

$$N_T = \mathrm{NRE} + \mathrm{NTUB'} \cdot \left\| \frac{\mathrm{ST}}{\mathrm{TI}} \right\| \tag{26}$$

where the number of rounds to establish is

$$\mathrm{NRE} = \mathrm{NSE} \cdot \mathrm{NTUB} \tag{27}$$

This methodology for instantaneous sources has been implemented in a Fortran V code called MUNEXP, which is described elsewhere in this report.

B. Continuous Sources.

1. Effective Screen Dimensions.

The lack of polar symmetry in continuous source plumes requires separate methodologies for the two primary line-of-sight orientations.

The only successful method to date for estimating crosswind screen lengths is a systematic search procedure based upon experience in prior efforts. If the emission rate is constant, which is assumed frequently in the absence of emission rate measurements, the screen length grows with time to a maximum length and reaches a steady state until emission stops. After burnout at $t = t_B$, the upwind end of the screen moves downwind until the screen vanishes. If the emission rate is not constant, the cloud must be simulated for an array of times to get the time trace of the ends of the screen. It is likely that the screen length will stabilize at some value during the burning time. If multiple sources are involved, stabilization is more likely since the cumulative effect of many clouds at different stages of growth tends to smooth the variations of individual clouds. The recommended procedure is to determine the screen length just prior to burnout. In most cases, the result is a screen length that is relatively stable and has existed for a large portion of the burning time. This screen length is the most significant measure of effectiveness for a munition because it usually forms in a short time and has significant durability and its location relative to the center of the impact zone is predictable for use by mission planners. The formation time can be estimated by dividing the distance to the downwind end of the screen by the average windspeed.

The location of the two ends of the screen should be sought independently. By choosing a small set of x distances which span a reasonable interval in which an end may be expected to lie, one can use a small number of simulations combined with an appropriate interpolation scheme to find the end sought. The expense of this procedure depends strongly on the accuracy required, but the accuracy of the simulation model should be considered before imposing resolution criteria.

For a headwind/tailwind situation, the effective screen width of a single continuous source is much smaller than in the crosswind case. If the screen must be established within a specified minimum time, the width at that time will likely be the minimum value for all later times less than the time at which the smoke emitted at $t = t_B$ reaches the front to be screened. Estimation of the effective screen width is accomplished by using the instantaneous source technique described earlier.

2. Munition Expenditure Requirements.

a. Crosswind Line of Sight.

Once an effective crosswind screen length is determined for a single munition or perhaps several munitions fired at the same aiming point, the construction of a screen to accomplish the mission must be undertaken. Again, because munition effectiveness is the prime objective, it is appropriate that the ability of troops to hit an aiming point be ignored. Therefore, a smoke screen

can theoretically be constructed by placing smaller screen segments end to end. To avoid possible gaps in the screen, only 90 percent of the length of an effective segment is used, implying overlap of segments. Thus, if a screen of length FRONT is to be built of segments having length S, the minimum number of segments (or aiming points) required is

$$N_S = 1 + \| \frac{L}{.9S} \| \tag{28}$$

When a single round produces the screen segment S, the number of rounds required equals the number of segments. However, some small munitions, such as mortars, do not produce significant screens with a single round. In these cases, the segment length ought to be estimated for multiple rounds fired at a single aiming point. Delivery errors should be a part of this type of simulation. Operational considerations should drive the trade-off between the number of aiming points and the total number of rounds required toward the selection of fewer aiming points.

Long burning times of continuous sources usually do not cause conflict with the fire rate of the unit. Therefore, munition expenditure requirements are obtained as the product of N_S and the number of rounds per segment, $N_{R/S}$:

$$NRE = N_S \cdot N_{R/S} \tag{29}$$

Maintenance of the screen is achieved by repeating the establishment fire at a time interval based on the burn time and formation time. Suppose the upwind end of the screen is formed at t_f seconds after function time. Then the screen exists for $t_B - t_f$ seconds, after which the edge begins to move downwind. If t_B seconds are allowed between fires, there is a possibility of a gap in the screen. If t_f is small, say $t_f < 10$ seconds, the combination of the 10 percent overlap and the arrival of clouds from upwind sources will probably suffice to allow the selection of t_B as the replenishment interval. If t_f cannot be ignored, let $t_B - t_f$ be the interval. The analyst may have to improvise if the screen length is not stable due to variable emission rates.

If the screen is to be maintained for a period of ST seconds, the total number of rounds required is

$$N_T = NRE \left(1 + \| \frac{ST}{t_B - t_f} \| \right) \tag{30}$$

This methodology is the simplest in concept and application; hence, no software is included in this report.

b. Headwind/Tailwind Line of Sight.

The problem of creating a screen under headwind/tailwind conditions is the most difficult. Fortunately, the frequency of occurrence in the real world of this situation is very low. Since each source produces a short screen at some specified time, the lateral distance between

sources is critical to the avoidance of clear "lanes" between plumes. For smoke generators with operators, it is a simple matter to place multiple generators at ideal sites for the desired screening effect. The methodology described here considers only rounds with multiple submunitions with random distribution of the impact points.

Assume the half-width of the screen produced by a single submunition is w, determined by the method in section III,A,1. Let x represent the crosswind axis with the origin being the center of the front to be screened. If all rounds are fired at the point (0,y), where y is the upwind distance from the front required to place the screen between the target and observer, the only distribution of impact points to be considered is that with respect to the x-axis.

For each round, we will assume n submunitions are distributed uniformly in an area bounded by a circle of radius R. The distribution of impact points with respect to x is given by the probability density function (pdf)

$$f(x) = \begin{cases} \dfrac{2}{\pi R^2} \sqrt{R^2 - x^2} & \text{for } |x| \leq R \\ 0 & \text{for } |x| > R \end{cases} \tag{31}$$

which assumes the center of the impact area to be at x = 0. It is preferable to rewrite this equation to represent the distribution of impact points u (parallel to x) centered at v:

$$f(u-v) = \begin{cases} \dfrac{2}{\pi R^2} \left[R^2 - (u-v)^2\right]^{1/2} & \text{for } |u-v| \leq R \\ 0 & \text{for } |u-v| > R \end{cases} \tag{32}$$

Let the front be represented as a set of points x lying in the interval (– FRONT/2, FRONT/2). The probability that an arbitrary point x is screened by one of the submunitions distributed by equation 32 is the probability that the distance between x and impact point u is less than the screen width w; i.e.,

$$\begin{aligned} P_1 &= P\left[\,|x-u| \leq w\right] \\ &= P\left[\,|u-x| \leq w\right] \\ &= P\left[-w \leq u-x \leq w\right] \\ &= P\left[x-w \leq u \leq x+w\right] \\ &= \int_{x-w}^{x+w} f(u-v)\,du \end{aligned} \tag{33}$$

Let $y = u - v$ to get

$$P_1\,(x, v) = \int_{x-w-v}^{x+w-v} f(y)\,dy \tag{34}$$

If equation 31 is used with equation 34, the result after integration is

$$P_1\,(x, v) = G\,(x + w - v) - G\,(x - w - v) \tag{35}$$

where

$$G(x) = \begin{cases} \displaystyle\int_0^x f(y)\,dy = \frac{1}{\pi R^2}\left[x\sqrt{R^2 - x^2} + R^2 \sin^{-1}\left(\frac{x}{R}\right)\right] & \text{if } |x| \leqslant R \\ \tfrac{1}{2} & \text{if } x > R \\ -\tfrac{1}{2} & \text{if } x < -R \end{cases} \tag{36}$$

The probability that the point x is screened by at least one of the n submunitions is

$$P_n\,(x, v) = 1 - [1 - P_1\,(x, v)]^n \tag{37}$$

If m rounds are fired at the aiming point, the probability of the point x being screened by at least one of the mn submunitions is

$$P_{nm}(x) = 1 - \prod_{i=1}^{m} \;[1 - P_n\,(x, v_i)] \tag{38}$$

The form of equation 38 is too involved to permit an analytic evaluation of $P_{nm}(x)$ or its expected value, which represents the fraction of the front which would be screened by m rounds. A Monte Carlo simulation technique can be used to evaluate

$$E\,(\text{FRONT},n,m,w) = \frac{1}{\text{FRONT}}\int_{-\text{FRONT}/2}^{\text{FRONT}/2} P_{nm}(x)\,dx \tag{39}$$

and

$$v(E) = \frac{1}{\text{FRONT}}\int_{-\text{FRONT}/2}^{\text{FRONT}/2} P^2{}_{nm}(x)\,dx - E^2 \tag{40}$$

Equation 40 is the variance of the expected screening coverage E.

The method used, which has been implemented in the computer program MUNX (described later), simulates repeated firings of m munitions at the aiming point and averages the results of the many experiments. The value of m is increased until E exceeds a specified value.

C. Comments on Methodology.

All of the techniques described above have the characteristic of overestimating expenditure requirements to an unknown degree because they neglect the screening effect of overlapping cloud regions outside the arbitrary boundary. This is done intentionally for several reasons:

1. To simplify analysis.

2. To compensate for assumptions of ideal round delivery.

3. To prevent unrealistic comparisons between munition systems in competitive studies.

The methodologies are based on idealized scenarios. Their validity in representing the real world has not been examined. It is assumed that their application would be valid for comparative effectiveness studies in which absolute effectiveness estimates are not required.

IV. COMPUTER PROGRAMS.

A. MUNEXP.

The program MUNEXP implements the methodology of section III, A, for instantaneous sources. The code is in Univac Fortran V and requires 8,357 words of user memory. The program is constructed in modular form to facilitate user modification of the half-width model. The input format is free-field to permit easy use of a demand terminal. For the same purpose, all output is restricted to 70-character lines.

Consider as an example the following screening mission. A 200-meter front must be screened below 10 percent transmittance within 45 seconds of the arrival of the first of many 155-mm M110 WP smoke projectiles. The wind is blowing toward the front at an angle of 30° and a speed of 10 mph. The meteorological stability is Pasquill category C (neutral). The relative humidity is 50 percent. The mission is to be accomplished by two artillery batteries with eight tubes each. Each battery carries 200 rounds into the field. The crews are capable of firing one round every 15 seconds for up to 4 minutes. The screen, once established, should be maintained for 4 to 8 minutes. The estimated target-observer range is 1500 meters. The questions to be addressed by the analyst are:

1. Can the mission be accomplished?

2. If so, how many rounds are required?

3. Where should the rounds be aimed?

4. How can the screen be maintained?

5. How long can the screen be maintained?

The first step in the analysis is the estimation of the half-width of a single round. The round is simulated under the given meteorological conditions to generate a matrix of CL values, shown in table 1, with the interpolated estimates of the half-width corresponding to a CL of 693 mg/m^2 shown in the augmented column. For WP, this CL will give a 10 percent transmittance in the visible wavelengths.

Using the x* values of table 1 as the half-widths at the times given, a least-squares fit with a 4-th degree polynomial model produces the curve shown in figure 1. From this curve, one can estimate that the maximum width occurs at t = 120, which is the input value for TM. The equation of the model is given at the top of figure 1, the coefficients being the A(I) input.

Applying all the information given to the computer program MUNEXP produces the output shown in figure 2, which includes the input data and the solution. The output indicates three rounds are to be fired at the required aiming points, but only the third point is required for replenishment every 22.5 seconds. The screen can be maintained for 90 minutes, requiring a total of 13 to 24 rounds for a 4- to 8-minute screen.

Most variable names in MUNEXP correspond to the notation of this report, but the code may not always use a variable name exclusively as used in the text. Table 2 gives the input variables, format, and definitions required for using the program. Table 3 shows the external subroutines required and their function. The listing of the code in figure 3 includes the routines used for the example problem.

B. MUNX.

The program MUNX implements the methodology described in section III,B,2 for continuous sources with a headwind/tailwind line of sight. The code is written in Univac Fortran V and requires 8800 words of user memory. Like MUNEXP, the I/O format is designed for user convenience and use of demand terminals; input is free field and output is limited to 70 characters.

For an example problem, consider the requirements to form a screen 125 meters long using the 155-mm M116 HC projectile. The screen must be formed 45 seconds after impact. Under 10 mph, category B (lapse) conditions, each of four submunitions produces a 3.8-meter screen at 45 seconds. The delivery errors are assumed to be $\sigma_{range} = 4$ and $\sigma_{deflection} = 3$. The four submunitions fall within 74 meters of the impact area center 95 percent of the time.

To get a 125-meter screen with 100 percent probability is impossible under this methodology. It is reasonable to ask for 95 percent certainty and not unreasonable to think the corresponding real world experiment would give a larger screen. Hence, we will choose EMIN = .95. We will seek a precision level of three significant digits in the integration procedure. This requires EPS to be 5×10^{-4}. To prevent excessive run time, we will choose NREP = 30, NMAX = 20, and MMAX = 30.

Table 1. Matrix of CL Values

t/x =	15	20	25	30	35	40	45	50	55	60	x*
2	22500	6580	1350	195	0	0	0	0	0	0	26.72
12	20900	10100	3970	1270	328	69	0	0	0	0	32.24
22	16400	10000	5340	2470	996	349	106	28.1	0	0	36.73
32	12600	8800	5560	3180	1640	762	320	122	41.6	12.9	40.55
42	9800	7450	5240	3400	2050	1140	585	278	122	49.7	43.73
52	7780	6250	4720	3350	2230	1400	830	455	236	115	46.50
62	6300	5270	4180	3160	2260	1540	999	614	359	199	48.76
72	5190	4470	3680	2910	2200	1600	1110	738	470	287	50.69
82	4350	3820	3240	2650	2090	1590	1160	823	560	368	52.23
92	3690	3300	2860	2400	1960	1540	1180	873	626	435	53.47
102	3160	2870	2540	2180	1820	1480	1170	897	670	487	54.42
112	2750	2520	2260	1970	1680	1400	1140	899	695	524	55.05

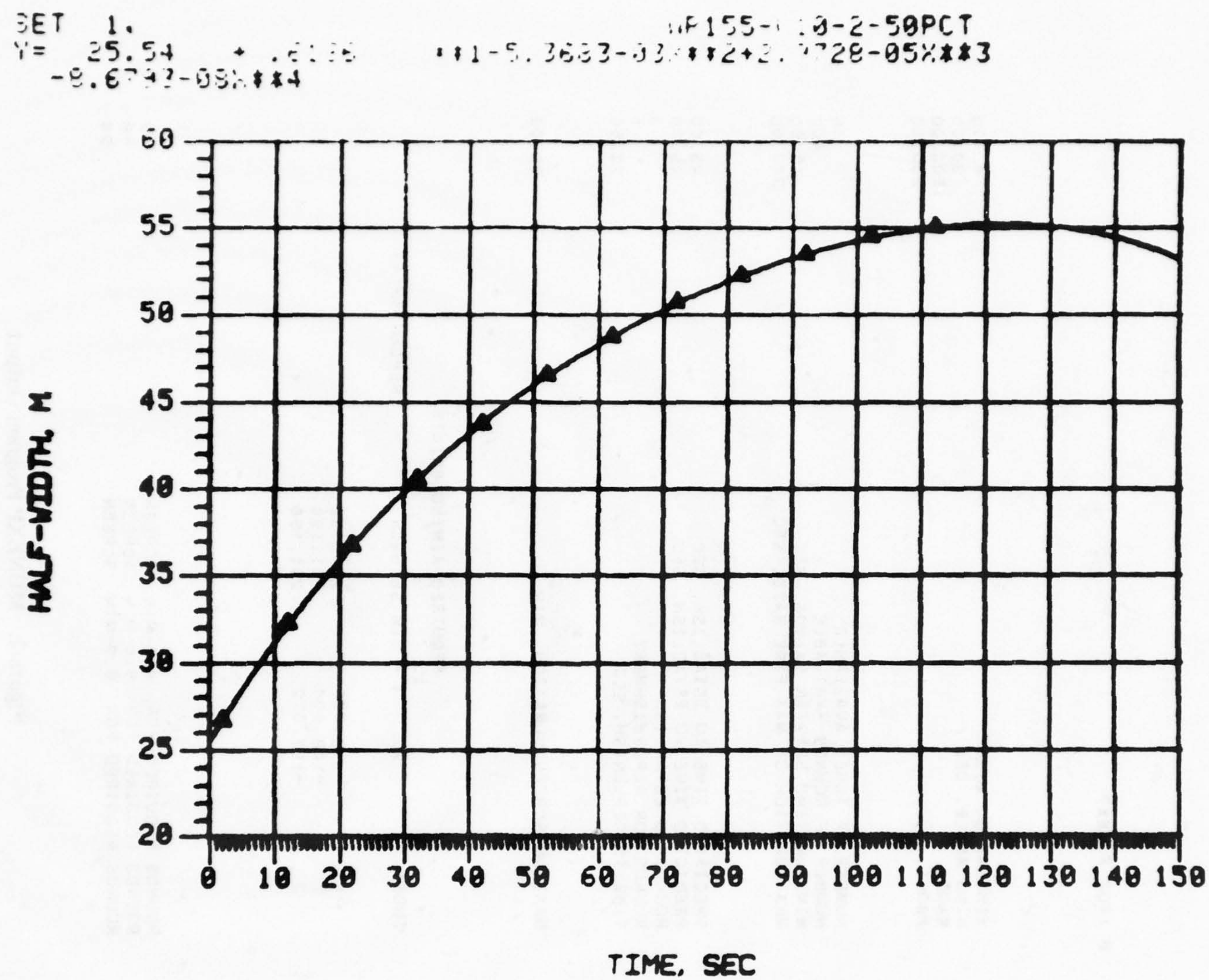

Figure 1. Sample Half-Width Curve

```
● :XQT F.MEXP


WINDSPEED, M/SEC                                                   4.470
WIND ANGLE, DEG                                                    30.00
RANGE, M                                                         1500.00
FRONT, M                                                          200.00


NUMBER OF TUBES AVAILABLE                                             16
NUMBER OF ROUNDS AVAILABLE                                           400
MINIMUM TIME BETWEEN SALVOS, SEC                                   15.00
MAX DURATION OF MAX FIRE RATE, SEC                                240.00


SPECIFIED TIME TO ESTABLISH, SEC                                   45.00
PREDICTED TIME TO ESTABLISH, SEC                                   45.00
ROUNDS TO ESTABLISH                                                    3
ROUNDS FOR REPLENISHMENT                                               1
TIME TO REPLENISH, SEC                                             22.50


MAXIMUM SCREEN DURATION, MIN                                       90.00


                       REQUIRED AIMING POINTS

INDEX          X       Y = MIN SETBACK          REPLENISH(*)


   1        -18.835         201.150
   2       -108.104         201.150
   3       -197.372         201.150                *


ROUNDS REQUIRED FOR  4.0-MIN  SCREEN                                  13
ROUNDS REQUIRED FOR  6.0-MIN  SCREEN                                  18
ROUNDS REQUIRED FOR  8.0-MIN  SCREEN                                  24
```

Figure 2. MUNEXP Program Output

Table 2. MUNEXP Input

Card No.	Variable	Type	Definition
1	M	Integer	Number of parameters in half-width model.
	KT	Integer	Number of screen duration times.
2	A(I) I=1,2,..M	Real	Parameters of half-width model.
	TM	Real	Estimate of time of maximum half-width, sec.
3*	FRONT	Real	Length of front, m.
	U	Real	Windspeed, m/sec.
	TO	Real	Required minimum formation time, sec.
	DANG	Real	Wind angle with front, degree $\leq 90°$.
	RNGE	Real	Observer-target distance, m.
4*	NTUB	Integer	Number of available delivery systems; default value is 1000.
	LD	Integer	Number of available rounds; default value is 10000.
	TMU	Real	Minimum firing interval, sec; default value is 1.
	TUM	Real	Maximum duration of maximum fire rate, sec; default value is 1000.
5*	ST(J) J=1,2,..KT	Real	Screen duration times, min.

*Cases can be stacked by repeating cards 3-5.

Table 3. MUNEXP Subroutines

Name	Call	Function
HW	F=HW(T)	Computes value of half-width model at time T.
DHW	F=DHW(T)	Computes derivative of half-width function at time T.
HTI	F=HTI(T)	Evaluates left-hand-side of equation 15.
NR	CALL NR(X,FCT)	Newton-Raphson routine to solve FCT(X) = 0.
DRDIFF	CALL DRDIFF (DYDX, FCT, X)	Evaluates derivative of FCT at X.

```
SAD*CMOKEX(1).MUNEXP
      DIMENSION ST(10),X(200),Y(200)
      COMMON/ONE/M,A(10)
      COMMON/TWO/ IN,FRONT
      DATA NTUBE,LOD,TTMU,TTUM/1000,10000,1.,1000./
      EXTERNAL HW,DHW,HTI
      READ(5,100) M,KT
      READ(5,100) (A(I), I=1,M),TM
   10 READ(5,100,END=99) FPONT,U,TO,DANG,RNGE
      READ(5,100) NTUB,LD,TMU,TUM
      IF(NTUB.LE.0) NTUB=NTUBE
      IF(LD.LE.0) LD=LOD
      IF(TMU.LE.0.) TMU=TTMU
      IF(TUM.LE.0.) TUM=TTUM
      WRITE(6,105) U,DANG,RNGE,FRONT
      WRITE(6,111) NTUB,LD,TMU,TUM
      RANG=DANG*3.1415927/180.
      UX=U*COS(RANG)
      UY=U*SIN(RANG)
      ST(1)=10.
      IF(KT.GT.0) READ(5,100) (ST(I), I=1,KT)
      TP=AMIN1(TO,(RNGE-100.)/(2*UY+.01))
      CALL NR(TM,DHW)
      TSTAR=AMIN1(TP,TM)
      AN=.5*FRONT/HW(TSTAR)
      N=AN
      IF(AN-N.GT.0.) N=N+1
      METH=2
      NSEMAX=1+TSTAR/TMU
      IF(N.LE.NTUB) METH=1
      IF(METH.EQ.1) GO TO 50
      AN=N
      NSE=AN/NTUB+.999
      NSET=NSEMAX+1
   11 NSET=NSET-1
      HT=HW(TSTAR-TMU*(NSET-1))
      NOLAP=.5*UX*TMU/HT
      NP=NSET*(NTUB-NOLAP)+NOLAP
      G=(NOLAP+(NTUB-NOLAP)*NSET)*HT-.5*FRONT
      IF(G) 13,12,11
   13 IF(NSET.GE.NSEMAX) GO TO 30
      NSET=NSET+1
   12 HT=HW(TSTAR-TMU*(NSET-1))
      NOLAP=.5*UX*TMU/HT
      NP=NSET*(NTUB-NOLAP)+NOLAP
      IF(HT.LT..5*FRONT/NP) GO TO 30
      TP=0
      NSE=NSET
   14 NIMAX=NSEMAX-NSE
      TS=TMU*(NSE-1)+TP
      TSTAR=AMAX1(TS,TO)
      TI=AMAX1(TMU,TSTAR/NSE)
      TUMP=TUM*TI/TMU
      NSEP=1+MIN(TUMP,TM-TP)/TMU
      NIMAX=NIMAX+(NSEP-NSEMAX)
      HT=HW(TSTAR-TI*(NSE-1))
      NTUBP=NTUB
      IF(NOLAP.GE.NTUB) GO TO 40
```

Figure 3. MUNEXP Program Listing

```
      GO TO 70
   30 TP=TM*.9
      IN=NP
      WRITE(6,130)
      IF(HTI(TM).LT.0.) GO TO 40
      CALL NR(TP,HTI)
      TP=TP+TMU*(NSE-1)
      IF(TP.GT.TM) GO TO 40
      NSEMAX=1+AMIN1(TUM,TM-TP)/TMU
      TP=TP-TMU*(NSE-1)
      NSE=NSET
      IF(NSE.LE.NSEMAX) GO TO 14
   40 WRITE(6,140)
      GO TO 10
   50 NIMAX=TUM/TMU-1
      NSE=1
      NSR=1
      IF(NIMAX.GT.1) NSR=2
      HT=HW(TSTAR)
      I=AN
   51 TP=(FRONT-(2*I-1)*HT-UX*TSTAR)/(UX+1.E-5)
      IF(TP.LE.TM) GO TO 52
      I=I-1
      IF(I.LE.1) GO TO 52
      GO TO 51
   52 NTUBP=N-I+(1+(NSR-1)*SIN(RANG))/NSR
      NTUBP=MAX(1,NTUBP)
      TI=TSTAR/NSR
      NIMAX=NIMAX*NTUB/NTUBP
      NTUB=N
   70 NIMAX=MIN(NIMAX,(LD-NSE*NTUB)/NTUBP)
      TMAX=NIMAX*TI/60.
      NRE=NSE*NTUB
      WRITE(6,104) TO,TSTAR,NRE,NTUBP,TI
      WRITE(6,110) TMAX
      IF(NSE.EQ.1) GO TO 80
      WRITE(6,114)
      GO TO 81
   80 WRITE(6,107)
   81 K=0
      IF(NOLAP.EQ.NTUB) NSE=1
      DO 86 L=1,NSE
      DO 85 J=1,NTUB
      K=K+1
      REP=' '
      IF(J.GT.NTUB-NTUBP) REP='*'
      X(J)=FRONT-(2*K-1)*HT-UX*TSTAR
      Y(J)=UY*(TSTAR+TI*(NSE-1))
      IF(METH.EQ.1) Y(J)=2*UY*TSTAR
      IF(NSE.GT.1) GO TO 83
      WRITE(6,108) J,X(J),Y(J),REP
      GO TO 85
   83 WRITE(6,113) L,J,X(J),Y(J),REP
   85 CONTINUE
      K=K-NOLAP
   86 CONTINUE
      WRITE(6,112)
      DO 90 J=1,KT
```

Figure 3. (Continued)

```
      IF(ST(J).GT.TMAX) GO TO 95
      K=60.*ST(J)/TI-.01
      NT=NRE+K*NTUBP
      WRITE(6,106) ST(J),NT
      GO TO 90
   95 WRITE(6,109) ST(J)
   90 CONTINUE
      GO TO 10
   99 STOP
  100 FORMAT()
  105 FORMAT(1H0,////,2X'WIND SPEED, M/SEC',T60,F10.3,/,
     *2X'WIND ANGLE, DEG.',T60,F10.2,/,
     *2X'RANGE, M',T60,F10.2,/,
     *2X'FRONT, M',T60,F10.2,///)
  104 FORMAT(
     *2X'SPECIFIED TIME TO ESTABLISH, SEC',T60,F10.2,/,
     *2X'PREDICTED TIME TO ESTABLISH, SEC',T60,F10.2,/,
     *2X'ROUNDS TO ESTABLISH',T60,I10,/,
     *2X'ROUNDS FOR REPLENISHMENT',T60,I10,/,
     *2X'TIME TO REPLENISH,SEC',T60,F10.2,///)
  106 FORMAT(2X'ROUNDS REQUIRED FOR',F5.1,' MIN. SCREEN',T60,I10)
  107 FORMAT(////,T24,'REQUIRED AIMING POINTS',//,
     *2X'INDEX',T17,'X',T24,'Y=MIN SETBACK',T47,'REPLENISH(*)',//)
  108 FORMAT(3X,I3,6X,F10.3,5X,F10.3,10X,A1)
  109 FORMAT(2X'ROUNDS REQUIRED FOR',F5.1,' MIN. SCREEN',T60,
     *'NOT AVAILABLE')
  110 FORMAT(2X'MAXIMUM SCREEN DURATION, MIN.',T60,F10.2)
  111 FORMAT(
     *2X'NUMBER OF TUBES AVAILABLE',T60,I10,/
     *2X'NUMBER OF ROUNDS AVAILABLE',T60,I10,/
     *2X'MINIMUM TIME BETWEEN SALVOS, SEC.',T60,F10.2,/
     *2X'MAX DURATION OF MAX FIRE RATE, SEC.',T60,F10.2,///)
  112 FORMAT(///)
  113 FORMAT(I8,8X,I3,6X,F10.3,5X,F10.3,10X,A1)
  114 FORMAT(////,T24,'REQUIRED AIMING POINTS',//,
     *2X'SALVO'5X'INDEX',T31,'X',T40,'Y=MIN SETBACK',T58,
     *'REPLENISH(*)',//)
  130 FORMAT(10X'SCREEN CANNOT BE ESTABLISHED BY FIRE UNIT IN'
     *,' SPECIFIED TIME.',//)
  140 FORMAT(10X'SCREEN EXCEEDS CAPACITY OF FIRE UNIT.')
      END
```

Figure 3. (Continued)

```
SAD*SMOKEX(1).NEWRAP
      SUBROUTINE NR(X,FCT)
      EXTERNAL FCT
      COMMON/C/IERR,F,N,NMAX
      NMAX=30
      IERR=0
      XO=X
      EPS=5.E-3
      N=1
    1 CALL DRDIFF(DFDX,FCT,XO)
      F=FCT(XO)
      EMIN=1.E-4
      IF(ABS(DFDX).LT.EMIN) DFDX=SIGN(EMIN,DFDX)
      DX=-F/DFDX
      X1=XO+DX
      ERR=ABS(DX)/(ABS(X1)+1.E-6)
      IF(ERR.LE.EPS) GO TO 5
      XO=X1
      N=N+1
      IF(N.LT.NMAX+1) GO TO 1
      F=FCT(X1)
      IF(ABS(F).LT..1) GO TO 5
      IERR=1
      N=N-1
    5 X=X1
      RETURN
      END
```

```
SAD*SMOKEX(1).DRDIFF
      SUBROUTINE DRDIFF(DFDX,FUNC,X)
      COMMON/D/HH
      DATA NB/4/
C     NB = 1/2 THE NUMBER OF DIGITS CARRIED BY THE MACHINE BEING USED
      F=FUNC(X)
      XX=X+HH
      D=.001*ABS(XX)
      IF(ABS(XX).LT.10.**(3-NB))D=10.**-NB
      H=AMIN1(F,D)
      DFDX=(FUNC(XX+H)-F)/H
      HH=0
      RETURN
      END
```

Figure 3. (Continued)

```
SAD*SMOKEX(1).WIDTH
        FUNCTION HW(T)
        COMMON/ONE/M,A(10)
        SUM=A(1)
        DO 1 I=2,M
      1 SUM=SUM+A(I)*T**(I-1)
        HW=SUM
        GO TO 10
        ENTRY DHW(T)
        SUM=A(2)
        DO 2 I=3,M
      2 SUM=SUM+A(I)*(I-1)*T**(I-2)
        HW=SUM
     10 RETURN
        END
```

```
SAD*SMOKEX(1).FUNCEX
        FUNCTION HTI(T)
        COMMON/TWO/ IN, FRONT
        HTI=HW(T)-.5*FRONT/IN
     10 RETURN
        END
```

Figure 3. (Continued)

Applying this information to the program MUNX produces the output in figure 4, which indicates 28 rounds are required to cover more than 95 percent of the 125-meter front. The variance in the expected coverage is 7.54×10^{-4}, which can be used to express the expected coverage as $.953 \pm .0275$. The output also says that 16 points were used in each integration to get an average relative error of 6.94×10^{-5} in the coverage estimate. The variance within the 30 replications is shown in the last column to provide insight to the range of coverage values observed.

This computer run required nearly 3 minutes of CPU time on the Univac 1108 computer, indicating that user input causing premature termination could be expensive. There are ways to accelerate the procedure which will be implemented in future work.

Input format and variables are shown in table 4. Table 5 gives the external subroutines and their functions. Some additional comments are required for clarification. The methodology is an iterative technique which converges if an answer is possible but terminates if user-specified limits are reached. The run time is dependent upon the input values of several variables: NC, NREP, MMAX, NMAX, EPS, and EMIN. The user will learn by experience how to choose reasonable input values. The example problem may provide some insight.

In the program listing of figure 5, the routine VRAND calls upon the routine GGNOF, which is not listed because it is a proprietary program from the International Mathematical and Statistical Library. The properties of GGNOF are the return of a random normal deviate with zero mean and unit variance. The seed, IS, is changed with each call of the routine. The function VRAND converts the deviate to one with standard deviation SIG.

The input value of SIG should be the root-mean-square value of the range and deflection standard deviations; i.e.,

$$\text{SIG} = \left(\sigma^2_{\text{range}} + \sigma^2_{\text{deflection}}\right)^{1/2} \tag{41}$$

This choice removes the effect of wind direction relative to the line of flight.

V. SUMMARY.

Methodologies have been developed and, where possible, implemented in computer programs for estimating smoke munition expenditure requirements under a broad range of operational conditions. The techniques are based on idealized geometries and simplifying assumptions which are expected to over-estimate requirements by an undeterminable margin. Validation of the estimates is desirable but has not been attempted. The techniques are designed to be used with any smoke-effect simulation model capable of providing information on effective screen size as a function of time.

```
@ :XQT F.MUNX
 RANDOM NUMBER SEED                                          1234567
 INITIAL POINTS                                                   10
 REPLICATIONS                                                     30
 MAXIMUM ROUNDS                                                   30
 MAXIMUM POINTS                                                   20
 MAXIMUM RELATIVE ERROR                                      .500-03
 SUBMUNITIONS PER ROUND                                            4
 RADIUS OF IMPACT ZONE, M.                                     74.00
 HALF-WIDTH OF SUBMUNITION SCREEN, M.                          1.900
 LENGTH OF FRONT, M.                                          125.00
 DELIVERY ERROR(SIGMA), M.                                      5.00
 MINIMUM COVERAGE                                               .950

     ROUNDS  COVERAGE VARIANCE    POINTS    REL. ERR.   REP. VAR.
        1    .107+00   .301-03     16       .249-03     .965-06
        2    .204+00   .859-03     16       .144-03     .525-06
        3    .288+00   .156-02     16       .141-03     .186-05
        4    .365+00   .223-02     16       .143-03     .741-06
        5    .432+00   .276-02     16       .141-03     .148-05
        6    .492+00   .326-02     16       .143-03     .154-05
        7    .546+00   .358-02     16       .135-03     .129-05
        8    .594+00   .382-02     16       .139-03     .425-05
        9    .637+00   .382-02     16       .127-03     .180-05
       10    .675+00   .385-02     16       .128-03     .191-05
       11    .709+00   .378-02     16       .125-03     .112-05
       12    .739+00   .370-02     16       .124-03     .139-05
       13    .766+00   .349-02     16       .119-03     .452-06
       14    .791+00   .328-02     16       .117-03     .682-06
       15    .812+00   .307-02     16       .112-03     .617-06
       16    .832+00   .285-02     16       .110-03     .617-06
       17    .849+00   .259-02     16       .103-03     .518-06
       18    .864+00   .241-02     16       .102-03     .551-06
       19    .878+00   .214-02     16       .983-04     .288-06
       20    .890+00   .196-02     16       .942-04     .469-06
       21    .902+00   .177-02     16       .932-04     .370-06
       22    .912+00   .157-02     16       .894-04     .345-06
       23    .920+00   .142-02     16       .846-04     .288-06
       24    .928+00   .125-02     16       .809-04     .271-06
       25    .936+00   .112-02     16       .787-04     .337-06
       26    .942+00   .983-03     16       .771-04     .181-06
       27    .948+00   .863-03     16       .725-04     .206-06
       28    .953+00   .754-03     16       .694-04     .148-06
```

Figure 4. MUNX Program Output

Table 4. MUNX Input

Card No.	Variable	Type	Definition
1	IS	Integer	Random number seed, odd integer.
	NC	Integer	Initial number of points for midpoint integration scheme.
	NREP	Integer	Number of replications.
	MMAX	Integer	Maximum number of rounds.
	NMAX	Integer	Maximum value of NC.
	EPS	Real	Maximum allowable relative error in integration.
2	N	Integer	Number of submunitions per round.
	R	Real	Radius of impact area (one round), m.
	W	Real	Half-width of one submunition screen, m.
	L	Real	Length of front, m.
	SIG	Real	Standard deviation of delivery system, m.
	EMIN	Real	Minimum expected fractional coverage of front.

Table 5. MUNX Subroutines

Name	Call	Function
G	F = G(X,R)	Evaluates function of equation 36.
VRAND	F = VRAND (IS,SIG)	Generates random normal deviate from distribution N (0,SIG).

```
SAD*SMOKEX(1).MUNX
          DIMENSION V(1000)
          REAL L
          READ(5,100) IS,NC,NREP,MMAX,NMAX,EPS
        1 READ(5,100,END=99) N,R,W,L,SIG,EMIN
          WRITE(6,101) IS,NC,NREP,MMAX,NMAX,EPS,N,R,W,L,SIG,EMIN
          WRITE(6,103)
          L=.5*L
          DO 50 M=1,MMAX
          EER=0
          SEE=0
          SE=0
          SV=0
          DO 40 NRP=1,NREP
          DO 10 I=1,M
       10 V(I)=VRAND(IS,SIG)
          EEE=0
          NP=NC
       11 EE=0
          VR=0
          DO 15 J=1,NP
          X=-L+(2*J-1)*L/NP
          PR=1
          DO 20 K=1,M
          A=X-W-V(K)
          B=X+W-V(K)
          P=1-G(B,R)+G(A,R)
          PR=PR*P
          IF(PR.LE.0.) GO TO 21
       20 CONTINUE
       21 EE=EE+PR**N
       15 VR=VR+PR**(2*N)
          EEF=1-EE/NP
          ERR=ABS(EEF-EEE)/(EEF+1.E-20)
          IF(ERR.LT.EPS) GO TO 25
          EEE=EEF
          NP=NP+1
          IF(NP.LE.NMAX) GO TO 11
       25 NC=NP-1
          EER=EER+ERR
          VR=VR/NP-(EEF-1)**2
          SE=SE+EEF
          SEE=SEE+EEF**2
       40 SV=SV+VR
          E=SE/NREP
          VAR=SV/NREP
          ER=EER/NREP
          RVAR=(SEE-NREP*E**2)/(NREP-1)
          WRITE(6,102) M,E,VAR,NP,ER,RVAR
          IF(E.GE.EMIN) GO TO 60
       50 CONTINUE
       60 GO TO 1
       99 STOP
      100 FORMAT()
      102 FORMAT(5X,I5,2E10.3,5X,I5,2E12.3)
      103 FORMAT(//,5X'ROUNDS',T14,'COVERAGE',T23,'VARIANCE',T35,
         *'POINTS',T45,'REL. ERR.',T56,'REP. VAR.')
      101 FORMAT(' RANDOM NUMBER SEED',T60,I10,/,
```

Figure 5. MUNX Program Listing

```
     *' INITIAL POINTS',T60,I10,/,
     *' REPLICATIONS',T60,I10,/,
     *' MAXIMUM ROUNDS',T60,I10,/,
     *' MAXIMUM POINTS',T60,I10,/,
     *' MAXIMUM RELATIVE ERROR',T60.E10.3,/,
     *' SUBMUNITIONS PER ROUND',T60,I10,/,
     *' RADIUS OF IMPACT ZONE, M.',T60,F10.2,/,
     *' HALF-WIDTH OF SUBMUNITION SCREEN, M.',T60,F10.3,/,
     *' LENGTH OF FRONT, M.',T60,F10.2,/,
     *' DELIVERY ERROR(SIGMA), M.',T60,F10.2,/,
     *' MINIMUM COVERAGE',T60,F10.3)
      END
```

```
SAD*SMOKEX(1).MUNXG
      FUNCTION G(X,R)
      IF(X.GE.R) GO TO 5
      IF(X.LE.-R) GO TO 10
      G=X*SQRT(R**2-X**2)+R**2*ASIN(X/R)
      G=G/(3.1415927*R**2)
    1 RETURN
    5 G=.5
      GO TO 1
   10 G=-.5
      GO TO 1
      END
```

```
SAD*SMOKEX(1).MUNXRAND
      FUNCTION VRAND(IS,SIG)
      VRAND=SIG*GGNOF(IS)
      RETURN
      END
```

Figure 5. (Continued)

VI. CONCLUSIONS AND RECOMMENDATIONS.

Use of the methodologies and computer programs in this report has not produced any estimates which appear unreasonable to the author, who has witnessed dynamic test firings of many smoke munitions. However, there is no familiarity with the capabilities of fire units to perform in a manner compatible with the methodology assumptions. For this reason, the only recommendation to be made is that analysts with the required expertise should evaluate the proposed methodologies from their own perspective and report the evaluation in the literature.

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Author: Ronald O. Pennsyle

Date: April 1979

Classification: Unclassified

This report was forwarded to your installation on 25 April 1979.

Please make the following changes:

Page 12: Equation (8) should be

$$t' = \frac{(2i-1)H(t^*) + u_x t^*}{u_x} < t_m$$

Page 27: Line 78 should be

```
51  TP = ((2*I-1)*HT+UX*TSTAR)/(UX+1.E-5)
```

Henry J. Bielecki
HENRY J. BIELECKI
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